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SAFETY HAZARD ANALYSIS/

FAILURE MODES EFFECTS ANALYSIS

FOR THE

747 CLASSICS RETROFIT FUEL QUANTITY INDICATING SYSTEM

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1.0 SCOPE

This report provides the Safety Hazard Analysis/Failure Modes Effects Analysis (FMEA) for the 747 Classics Retrofit Fuel Quantity Indicating System (FQIS). The 747 Classics refers to all Boeing 747 models prior to the 747-400.

2.0 REFERENCE DOCUMENTS

<u>Simmonds Precision Products, Inc. Documents</u>.

4401000-26-01	747 Classics Retrofit FQIS System Requirements Specification
D-1827	Safety Hazard Analysis/FMEA for the 747-400 FQIS
D-2282	Safety Hazard Analysis/FMEA for the 757/767 FQIS
D-2230	Safety Hazard Analysis for the A330/A340 Indicator/Preselector & Tank Units

<u>Military Documents</u>.

MIL-STD-1629A	Procedures for Performing an FMEA
MIL-HDBK-217E	Reliability Prediction of Electronic Equipment
MIL-C-26988	General Specification for Liquid Quantity Gauge

<u>Other</u>

FAR Part 25	Federal Aviation Regulations, Part 25 - Airworthiness Standards: Transport Category
UL 913	Intrinsically Safe Apparatus and Associated Apparatus for use in Class I, II, III, Division 1, Hazardous (Classified) Locations
RTCA/DO-160C	Environmental Conditions and Test Procedures for Airborne Equipment

3.0 ITEM DESCRIPTIONS

3.1 <u>System and Components</u>

The 747 Classics Retrofit FQIS is comprised of the following subsystem components:

a) Fuel Quantity Processor Unit
b) Flight Engineer's Panel Indicators
c) Refuel Panel Indicators
d) Densitometers
e) Compensators
f) Capacitive Fuel Probes

The FQIS has the following functions:

- Measures the mass of fuel in each tank of the aircraft.
- Displays fuel mass per tank on individual cockpit indicators.
- Displays total fuel mass on board and gross aircraft mass on a separate cockpit indicator.
- Provides a means of selecting the units in which mass is displayed (as pounds or kilograms).
- Provides a means of manually setting gross aircraft mass display prior to takeoff.
- Controls ground refueling of the aircraft in total preselect and manual modes.
- Interfaces with and recognizes the fuel tank configuration of aircraft variants having from seven to ten tanks without modification.
- Provides fault detection, isolation and reporting to maintenance personnel via a BITE display and keyboard.

A block diagram for the FQIS is shown in Figure 1.

3.2 Fuel Quantity Processor Unit

The Fuel Quantity Processor Unit is an electrically operated device located in the electronic equipment bay. It is divided into three functional sections:

1. Individual Fuel Quantity Channels (IFQCs).
2. Input / Output Channels (IOCs).
3. Built In Test Equipment (BITE).

Each functional section consists of one or more Hardware Configuration Items (HWCIs) and an equivalent number of Computer Program Configuration Items (CPCIs). The individual printed wiring assemblies within each functional section are designated as Line Replaceable Units (LRUs) and are housed in a chassis. The processor chassis houses and provides internal and external connections for seven IFQCs, two IOCs, one relay module, one BITE module, and a BITE display panel.

3.2.1 Individual Fuel Gauging Channel (IFQC)

The IFQCs utilize inputs from capacitance tank units, compensators and densitometers within their tanks in order to determine fuel information, such as dielectric and density, which can then be utilized to compute the fuel quantities (volume and mass). Each IFQC computes the fuel quantities for its tank and transmits those values to the IOCs, which then pass the required information to the flight engineer's panel and refuel panel displays. The IFQC monitors IFQC LRU functionality, and transmits detected fault flags to the IOC for specific fault isolation. The IFQCs are also identical and interchangeable.

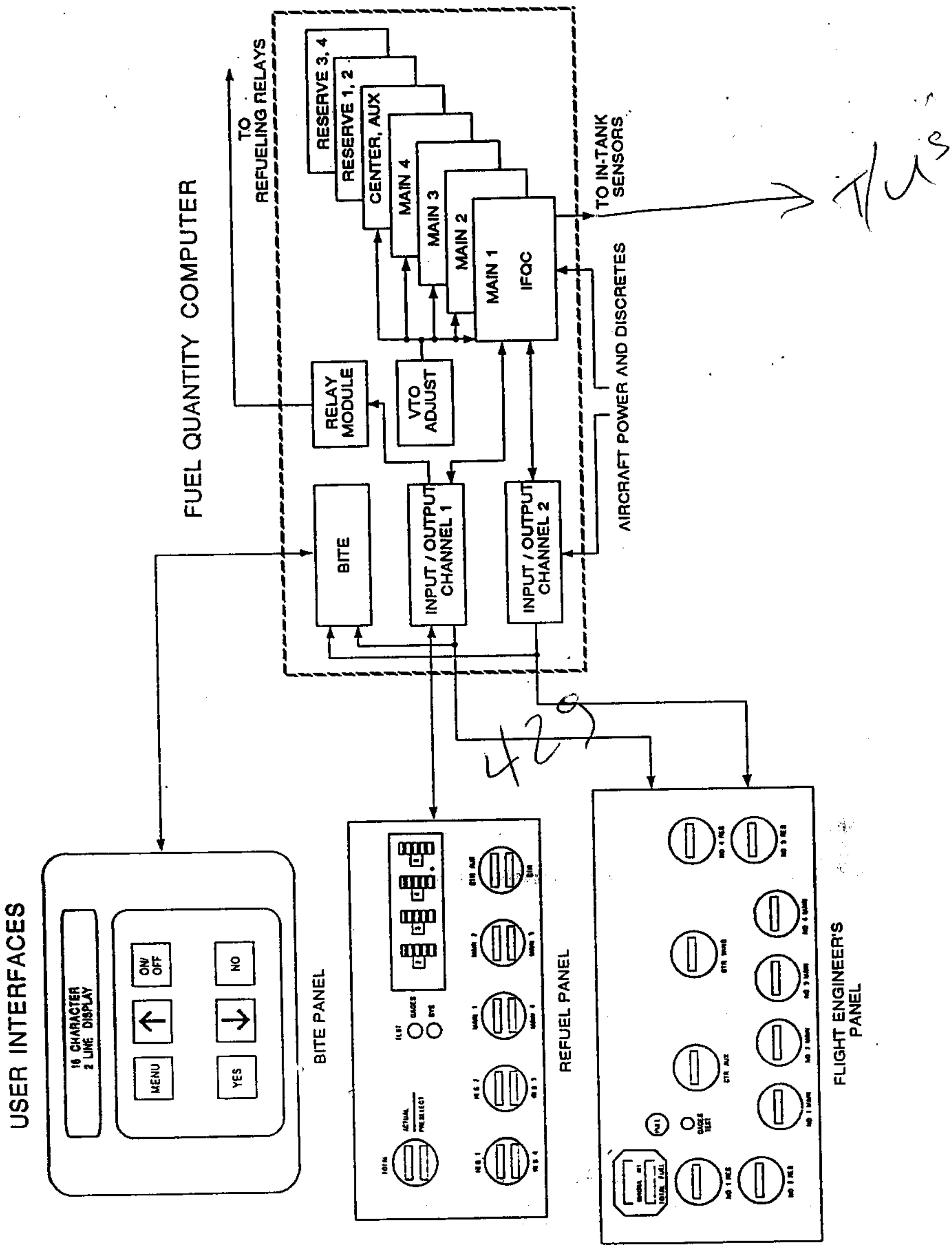


Figure 1 FQIS Block Diagram

[redacted]

3.2.2 I/O CHANNEL (IOC)

The two IOC cards are identical and interchangeable. The IOC, when in position one of the processor box, formats the output data for ARINC transmission on Bus A. The IOC, when in position two of the processor box, formats the output data for ARINC transmission on Bus B.

The IOC monitors components for fault conditions. Error messages set by the IFQC and IOC error flags will be evaluated to determine if system components are malfunctioning. If a component is inoperative or exceeding predetermined limits of operation, the IOC will set an ARINC message indicating this component has failed.

The IOC provides refuel calculation/control functions. Refueling may be performed using the manual or automatic method. During manual refueling, the IOC closes the valves for the tank when it reaches its volumetric shut-off (VSO). During automatic refueling, load select values are used. In this case, the operator selects the amount of fuel to be loaded into each tank using thumbwheel digits. When the actual tank value equals the load select value, the IOC will cause the valves to close.

The IOC is also responsible for the following functions:

* 3-Wire Discrete Excitation (IOC #1)

* Discrete Input Processing

* Tank Data Input

* Fuel Quantity Rate Limiting

* Fuel Uplift Calculation

* Total Fuel Quantity

* ARINC Data Formatting and Output

* Engineer's Panel Initiated Indicator Test

* Refuel Panel Initiated Indicator Test (IOC #1)

* Refuel System Test (IOC #1)

* Built in Test Functions

3.2.3 Bite board/ Display

The primary function of the BITE board/ display is to display fault data and system data on the front panel of the processor. The control of the display is via six front panel momentary push button switches. Data is received from the IOCs across ARINC busses, Bus A and Bus B.

3.2.4 Relay Board

The relay board LRU contains 10 relays that control the actuation of the refueling valves. The relay board accepts valve commands from both the IOC#1 an the fueling panel manual valve control switches. Both the IOC and the switch must command the valve "open" in order to open the valve. Otherwise, the valve will be "closed".

3.3 Flight Engineer's Panel

Individual fuel quantity indicators are located on the flight engineer's panel, one for each tank on the aircraft. Also located on the flight engineer's panel is a total fuel quantity indicator. This indicator also displays aircraft gross weight as set by the flight engineer via a panel mounted rotary control. Gross aircraft weight indication decrements in concert with total fuel quantity as fuel is used. Separate indicators are used to display each of the following:

* Total fuel/aircraft gross weight.

* Mains two and three.

* Mains one and four.

* Center and center auxiliary (if installed).

* Reserves one and four.

* Reserves two and three (if installed).

Except for the gross weight/ total fuel indicator on the engineer's panel, all indicators are identical in design and incorporate dual displays. These indicators are completely interchangeable with the indicators on the refuel panel. Each indicator has tank ID recognition programmed via discrete jumpers built into the mating connector wiring. Each indicator is capable of receiving ARINC 429 information for display over the two redundant ARINC busses. For individual tank indicators on the engineer's panel, the lower display is always blank.

3.4 Refuel Panel

The refuel panel incorporates displays and operator controls for both automatic and manual refueling modes. Up to six indicators are located on the refueling panel under the left wing and utilize both upper and lower displays. In addition, switches are provided to initiate refuel system test and refuel panel gauge test.

3.5 Densitometer

The densitometer measures the actual fuel density. There is one densitometer per main tank (center and mains one through four). Densitometers contain a vibrating spool and return a frequency signal that is directly proportional to the density of the fuel being measured.

3.6 Compensator

The compensators are specially designed concentric tube capacitors that are located near the lowest point in the tank and are normally covered with fuel. Compensators measure fuel dielectric and are used in conjunction with the densitometer to compensate for the difference in fuel density. A compensator is installed in each main tank (main 1 - main 4) the center wing tank, and reserve tanks one and four.

3.7 Capacitive Fuel Probes

The capacitive fuel probes are two concentric tubes (capacitors) mounted in the fuel tanks which provide a signal (Hi-Z) proportional to fuel height.

[redacted]

4.0 SAFETY/HAZARD STUDY

4.1 Intrinsic Safety Requirements

The energy stored by any equipment located inside a fuel tank or connected to in-tank equipment shall not exceed 0.02 millijoules per tank.

The current in any equipment located inside a fuel tank shall not exceed 0.010 amperes RMS under any normal operation or single fault in either the fuel tank equipment or in the fuel quantity processor unit including:

* Failure of any current limiting circuitry including insulation breakdown between tank and adjacent circuitry

* Short circuit of in-tank circuits between conductors or from any conductor to the airframe.

* A single power line fault in the interconnect, either to 115 VAC or 28 VDC.

Under any multiple fault scenario, the maximum power delivered to the tank shall not exceed the following values:

* 25.6 Volts peak open circuit

* 25.5 Milliamps RMS

* 165 Milliwatts

The temperature of any equipment directly exposed to fuel or fuel vapors shall not exceed 390°F (≈200°C) during any condition.

The sensor wiring shall be physically isolated from 115 VAC power wiring and refuel control wiring to preclude the possibility of intrinsically unsafe current/voltage levels entering the fuel tanks.

4.2 In-tank Current, Energy, & Power

The current in any compensator, fuel probe or densitometer does not exceed 10mA RMS, due to the duty cycle of the each signal to the tank and/or high circuit impedance, under the following conditions:

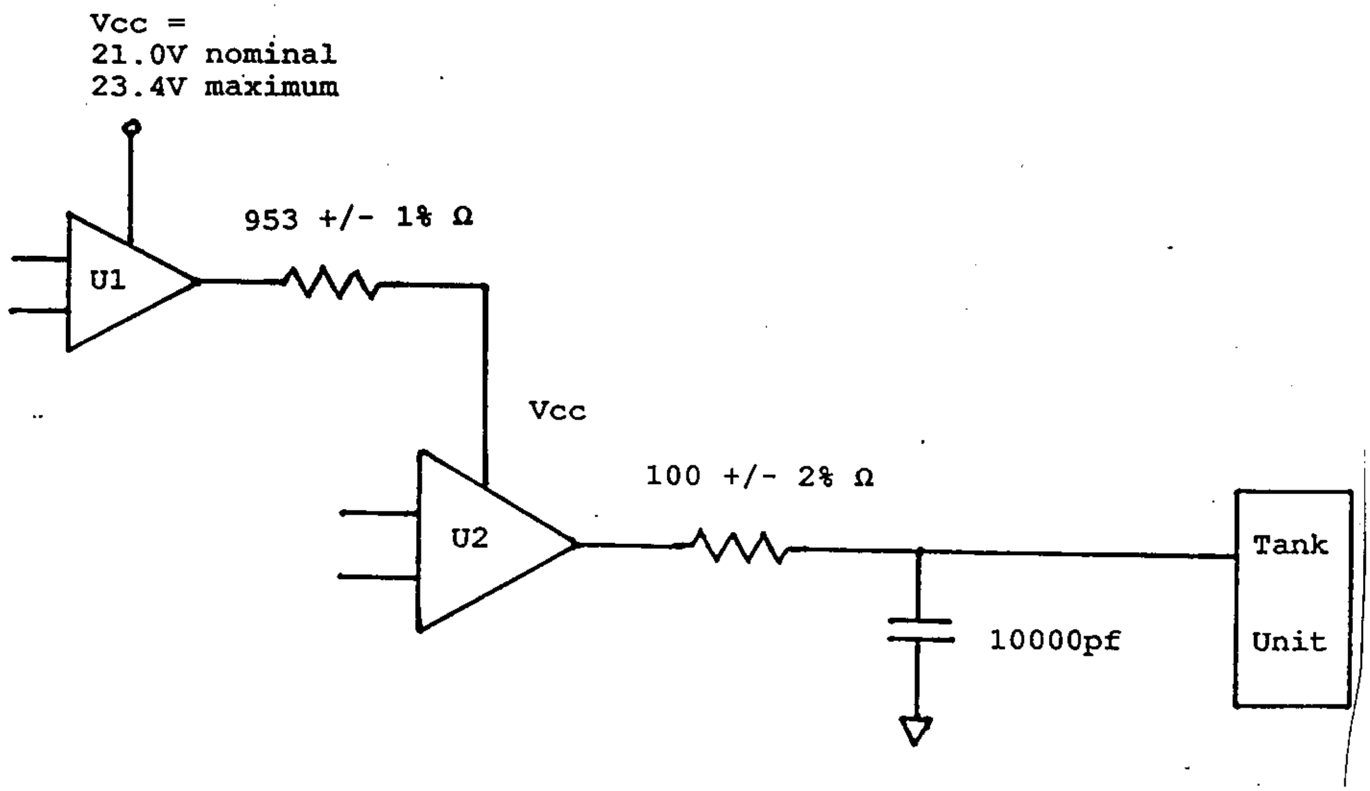
a) Normal operation of the equipment.

b) A single fault in either the fuel tank equipment or in the fuel quantity processor including: failure of any equipment in the current limiting circuit including insulation breakdown between tank circuitry and adjacent circuitry, or a short circuit of the tank circuits between conductors or from any conductor to the airframe.

c) A single power line fault in the interconnecting harnesses either to 115 VAC 400Hz or to 28 VDC.

Figure 2 and Figure 3 analyze the maximum current and maximum energy delivered to a fuel tank under multiple fault conditions. Figure 2 analyzes the failures for a compensator or fuel probe. Figure 3 analyzes the failures for a densitometer.

The maximum peak open circuit voltage to the tank is 23.4 volts and the maximum power dissipation in the tank is 33 mW (densitometer circuit, $(24.16\ \text{mA})^2 \times 57\Omega$).



Under worst case conditions, Vcc of U1 and U2 are shorted to their outputs and the return line from the tank unit (compensator or capacitive fuel probe) is shorted to ground; the resistor tolerances are worst case. The maximum current to the fuel tank unit is:

$$I_{max} = \frac{23.4\text{ V}}{(943.47 + 98)\Omega} = 22.47\text{ mA}$$

The maximum energy storage under worst case conditions is:

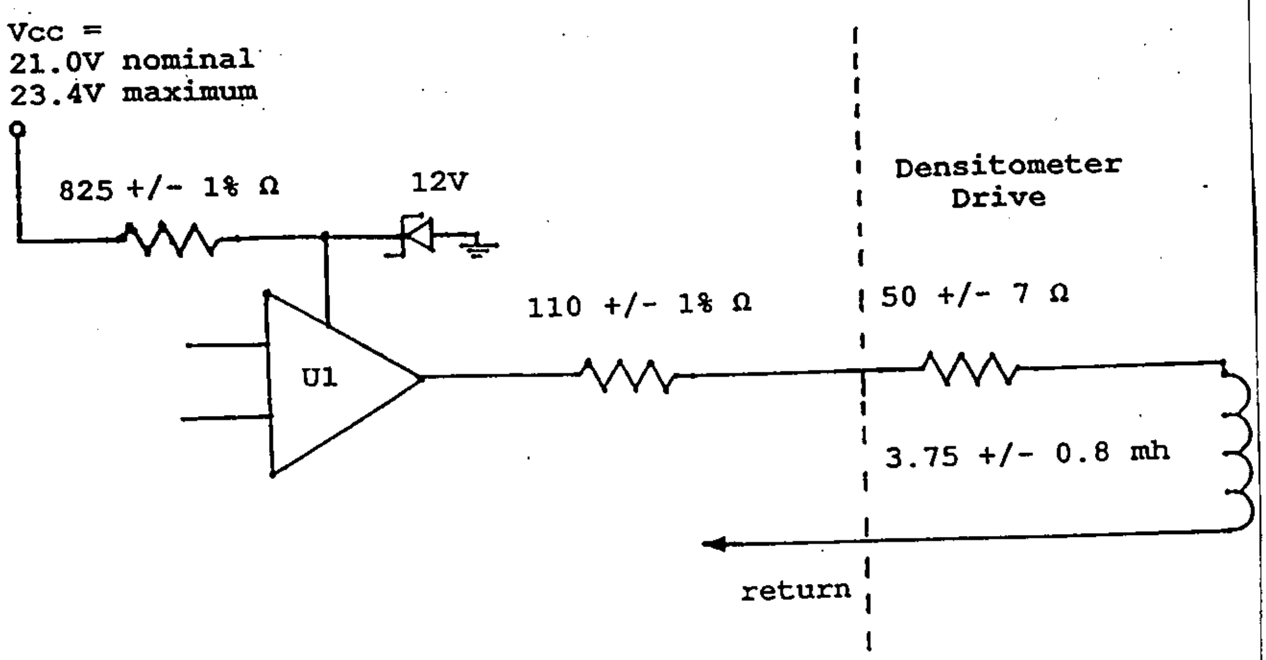
$E = \frac{1}{2}CV^2$, where C = capacitance of (motherboard + wire + probe)

$= \frac{1}{2}(10{,}000\text{ pf} + (200\text{ ft} \times 90\text{ pf/ft}) + 50\text{pf})(23.4\text{V})^2$

$= 0.008\text{ mJ}$

SAFETY ITEM	CURRENT (mA)	ENERGY STORAGE (mJ)
Compensator or Fuel Probe	22.47	0.008
Simmonds Precision Limit	25.5	0.020
Industry Limit	200	0.200

Figure 2 COMPENSATOR & FUEL PROBE MAXIMUM CURRENT & ENERGY



Under worst case conditions, Vcc of U1 is shorted to its output and the return line from the densitometer drive coil is shorted to ground; resistor tolerances are worst case. The maximum current to the densitometer in the fuel tank is:

$$I_{max} = \frac{23.4\ V}{(816.75 + 108.9 + 43)\Omega} = 24.16\ mA$$

With worst case current input to the drive coil and the drive coil of densitometer at worst case tolerance, the maximum energy storage to the densitometer in the fuel tank is:

$$E = ½Li^2$$

$$= ½(4.55\ mh)(24.16mA)^2$$

$$= .001\ mJ$$

SAFETY ITEM	CURRENT (mA)	ENERGY STORAGE (mJ)
Densitometer	24.16	0.001
Simmonds Precision Limit	25.5	0.020
Industry Limit	200	0.200

Figure 3 DENSITOMETER MAXIMUM CURRENT & ENERGY

4.3 Excessive Temperatures Within the Fuel Tanks

The densitometer's liquid density transducer was subjected to a test to determine change in resistance over change in current. The drive coil and sense coil of the transducer are copper wires in which resistance changes .38%/°C. Therefore, temperature rise can be calculated based on change in resistance from a low current to higher currents. The following table documents the test for both the drive coil and sense coil at room temperature in free air.

Current (ma)	Vdrive (V)	Rdrive (Ω)	Drive Temp Rise(°C)	Vsense (V)	Rsense (Ω)	Sense Temp Rise(°C)
1	.050461	50.4610	-	.099665	99.6650	-
10	.50975	50.9750	3	1.01336	101.3360	4
20	1.0216	51.0800	3	2.0302	101.5100	5
30	1.5365	51.2167	4	3.0703	102.3433	7
40	2.0719	51.7975	7	4.1364	103.4100	10
50	2.6263	52.5260	11	5.2465	104.9300	14
60	3.2023	53.3717	15	6.3966	106.6100	18
75	4.2242	56.3227	31	8.4902	113.2027	36
85	4.8875	57.5000	37	9.8344	115.6988	42

The voltage readings were taken when the unit stabilized after the currents were injected. The following equation was used to calculate the coil temperature rise:

$$\text{Temperature Rise} = \frac{\text{Rcoil(Xma)} - \text{Rcoil(1ma)}}{\text{Rcoil(1ma)} \times (0.0038)}$$

where X = 10ma thru 85ma

The maximum ambient temperature specified for the densitometer is 70°C. The maximum worst case current to the densitometer is 24.16 mA. For this current, the temperature rise above ambient can be as high as 7°C which results in a densitometer temperature of 77°C. This is well below the 200°C requirement for temperature of equipment within the fuel tank.

4.4 Other Safety Related Issues

Other safety related issues and observation made during this study included the following:

1) Toxic Materials - No toxic/carcinogenic materials are used in the design.

2) High Voltages - DC surge voltages as high as 80V for 10 milliseconds may be developed in the power input to the FQIS. These voltages, however, are not accessible to service personnel as installed in the aircraft and present no danger during normal operation. The only time these voltage levels are accessible is when the processor unit is opened with power applied for example for troubleshooting and/or repair purposes. Should this situation occur, appropriate precautions must be adhered to prevent personnel danger and equipment damage.

3) Electrostatic Discharge - Due to the use of Complementary Metal Oxide Semiconductor (CMOS) technology components, it is imperative that any shop repairs requiring the opening of the indicator will be performed at a static free workstation. As a minimum, personnel and workbenches should be properly grounded and paper, plastics and other static generating materials should be shielded or removed from the work area.

4.5 Safety Analysis Results.

The in-tank equipment has been found to be compliant with all requirements for maximum temperature, maximum current, maximum power, and maximum energy storage. The temperature analysis assumes the maximum ambient temperature of air in the fuel tanks is 70°C. Conformance to the approved installation procedures of the FQIS will ensure isolation of the tank sensor wiring from any 115 VAC power source on the aircraft.

5.0 FMEA SUMMARY

No major or catastrophic failure modes were found. In terms of severity, the most critical failure is the loss of a single IFQC which results in a display blanking for one tank and total display blanking on the Flight Engineer's Panel (FEP) or Refuel Panel (RP). Although the two IOC boards are identical, the loss of IOC #1 would have a greater impact. If IOC #1 fails, the following is lost: automatic preselect refueling, three wire discrete excitation, Refuel Panel Initiated Indicator Test, and Refuel System Test. Normal operation will continue with IOC #2 for all other FQIS functions.

No single or multiple failures of a tank circuit affect the fuel quantity data used for the FEP or RP, for more than one tank. If a detected failure is likely to result in a gauging error in excess of 5%, then the affected displayed quantities will be blanked. A fuel quantity error between empty and 5% tank capacity will be offset so that there is never a positive error displayed at empty.

No single detectable failure or detectable failure in combination with undetected failures will prevent the shutoff signal of at least one fueling valve in each tank (tanks with two fueling valves only). No single detectable failure will prevent an open signal from being provided to one fueling valve in each tank.

If there is any failure of the LBS/KGS program pin input, the processor will display data in the units identical to the discrete configuration in memory. If the discrete information from memory is invalid, the display will be in kilograms. However, if the discrete information from memory is invalid and the majority of IFQCs are sending LBS status, the display will be in pounds.

Loss of power to a FEP Indicator or RP Indicator will cause the display to blank. Loss of signal to these indicator will cause the display to blank. Failure in one indicator circuit will not cause an error or loss of read-out on the remaining indicators. No single failure will cause an unannounced shifting, on the displays, of the units from kilograms to pounds or vice versa.